ANALYSIS OF FUTURE HYDROPOWER DEVELOPMENT AND OPERATIONAL SCENARIOS ON THE ZAMBEZI RIVER BASIN

J.P. Matos[1], T. Cohen Liechti[1], and A.J. Schleiss[1]
1. Laboratory of Hydraulic Constructions, École Polytechnique Fédérale de Lausanne, Switzerland.

PRESENTER: ANTON J. SCHLEISS

ABSTRACT

The Zambezi River basin is the fourth largest in Africa. Covering an area of about 1 400 000 km^2 that is shared among 8 countries, it is the home of over 30 million people. There are ample opportunities for development in the region, including on the hydropower sector, whose estimated potential still to be exploited amounts to over 8 000 MW. In the future, the Zambezi is thought to be particularly vulnerable to climatic changes, with sizable expected impacts on average runoff, and will play a key role in the challenges posed by regional water scarcity. How future and current hydropower schemes are laid out and operate will affect the valuable ecosystems still thriving in the riparian areas of the basin and impact economic, as well as societal aspects. The present contribution employs a daily flow routing model in order to evaluate the impacts of different future hydropower development scenarios on the Zambezi River basin. Resorting to it and a multi-objective optimization technique the trade-offs between environmental and hydropower production concerns were clearly identified.

1. INTRODUCTION

1.1 Motivation and goals

Southern Africa, and the Zambezi River Basin (ZRB) in particular, are bound to face significant challenges related to their water resources in the coming decades. On the one hand growing population and booming economic activity will undoubtedly increase the pressure exerted on natural ecosystems, be it in terms of land use changes, direct water abstractions for irrigation, or increased evaporation from new hydropower schemes. On the other hand, studies indicate that climate change is likely to have a strong impact on the basin's climate and runoff characteristics (Intergovernmental Panel on Climate Change (IPCC), 2001). Presented what can be classified as worrying figures, Arnell (1999) found that the ZRB can witness decreased precipitation (~15%), increased potential evaporative losses (~15-25%), and diminished runoff (~30-40%).

The influence of large dams on the basin has been studied by a number of researches over the past years, notably by the African Dams Project (ADAPT) interdisciplinary group (Cohen Liechti, 2013; Mertens et al., 2013; Tilmant et al., 2010), from which this study stems. In fact, several of the existing dams in the ZRB have recently, or will in the future, be subject to hydropower production capacity increases and, consequently, be driven to review operation practices. In parallel, a number of new schemes are planned, both having the capacity to modify the runoff patterns of downstream areas. Notwithstanding, despite the efforts of governments, non-government organizations (e.g. Beilfuss and Brown, 2006; King and Brown, 2014), and the permanent establishment of the Zambezi Watercourse Commission (ZAMCOM), a consensus is yet to be achieved on the equilibrium between hydropower production and environmental concerns, namely in the form of prescriptions for environmental flows.

With the goal of assessing the effects of different dam operations on downstream flow characteristics, the present contribution employs a daily flow routing model in order to evaluate the impacts of different future hydropower development scenarios on the Zambezi River basin. Resorting to it and a multi-objective optimization technique the trade-offs between environmental and hydropower production concerns were clearly identified.

1.2 The Zambezi River basin and the studied hydropower systems

Running over 2 600 km, the Zambezi River is one of the great African rivers. The ZRB covers an area of about 1 400 000 km^2 that is shared among Angola (18.5%), Botswana (1.4%), Malawi (8.0%), Mozambique (11.8%), Namibia (1.2%), United Republic of Tanzania (2.0%), Zambia (41.6%), and Zimbabwe (15.6%) (SADC/SARDC et al., 2012). It is also the home of over 30 million people.

Within the ZRB there a number of valuable wetland areas of which the Barotse Floodplain, the Kafue Flats, and the Marromeu complex are examples. Co-existing with the latter are sizable dams with the capacity to significantly alter natural flow regimes (e.g. Cohen Liechti, 2013; Matos et al., 2010). The most important among them are the Kariba, Itezhi-Tezhi, and Cahora Bassa dams. A map of the basin, showing the location of its most notorious features and identifying the main subbasins, is presented in Figure 1.

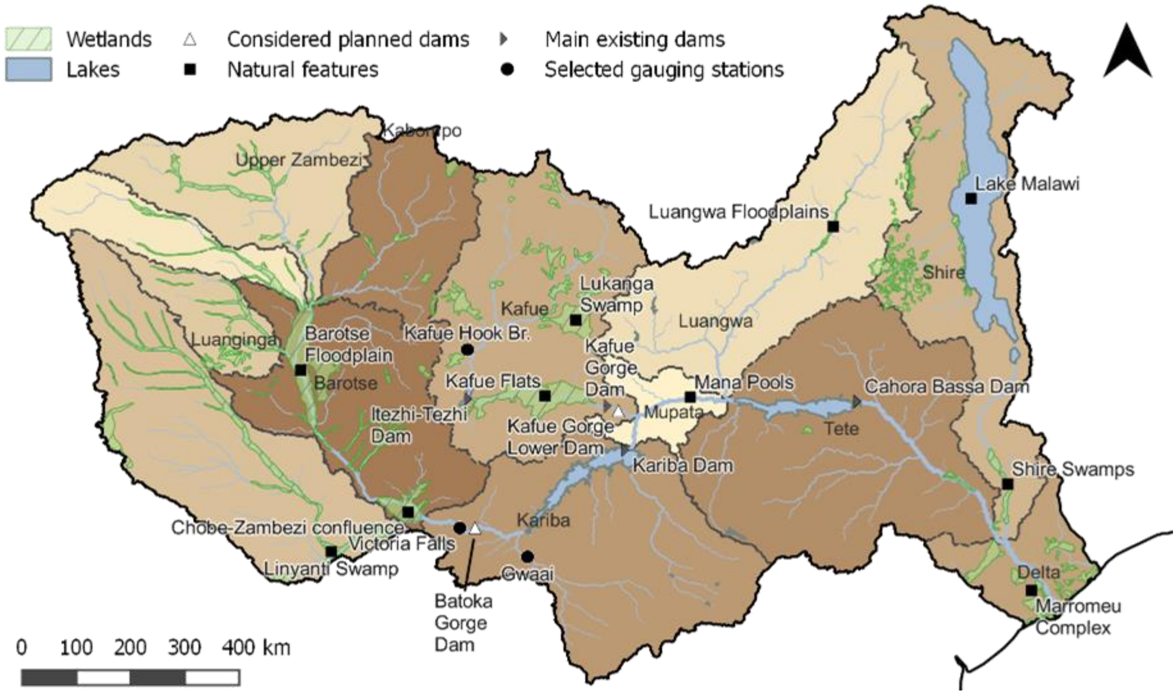

Figure 1. Map of the Zambezi River basin. Indication of main features and subbasin names.

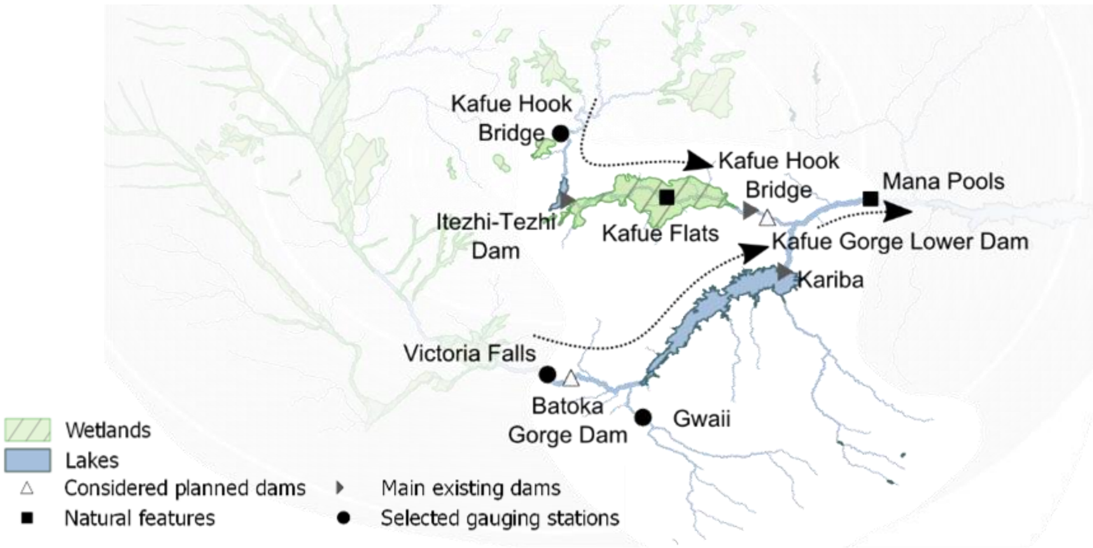

Figure 2. Scheme of the studied system.

The system addressed in this work is a subset of the whole basin. It is bound by the Kafue Hook Bridge on the North, by the Victoria Falls on the West, and by the Mana Pools, on the East. As illustrated in the scheme presented in Figure 2, it includes the Batoka Gorge, Kariba, Itezhi-Tezhi, Kafue Gorge, and Kafue Gorge Lower dams.

2. METHODOLOGY AND DATA

2.1 Overview

Having in mind the goal of assessing the effects of different dam operations on downstream flow characteristics, the inflows to the system were firstly quantified. These were based on discharge series at Victoria Falls (1958-2010), on the Zambezi River, Kamativi (1956-1984), on the Gwaai River, and Kafue Hook Bridge (1973-2010), on the Kafue River. The existing observations were then extended using a probabilistic method, the Generalized Pareto Uncertainty (Matos, 2014), in order to cover a concurrent period of 20 years.

A mass-balance model was prepared in order to route the flows through the system. Notably, it includes modules to simulate dam operations – including environmental flows – and wetlands. The former is described in section 0. The latter was used in order to simulate the effects of the Kafue Flats – the largest wetland within the system – on the flow between the Itezhi-Tezhi and Kafue Gorge dams. It implemented the floodplain modelling approach proposed by Cohen Liechti et al. (2014), according to which outflows are defined by eqs. (1), (2), and (3):

$$Q_{out} = Q_{base} + Q_{up} \tag{1}$$

$$Q_{base} = k \cdot h \tag{2}$$

$$Q_{up} = \begin{cases} a \cdot (h - h_{\min})^b & if\ h > h_{\min} \\ 0 & if\ h \le h_{\min} \end{cases} \tag{3}$$

where Q_{out} is the outflow from the floodplain, h is the water height, and k, a, b, and $h_{\min}$ are free parameters. In the present case these free parameters were fitted to daily data observed from 1981 to 2009.

In order to route the flow through the dams, information on their physical attributes and operational practices was required. Likewise, the physical features of the Kafue Flats were necessary. A detailed account of the characteristics that were adopted is given in Cohen Liechti (2013) and Matos (2014).

Based on the mass-balance model a range of environmental flow prescriptions and base outflows were tested. According to the perceived needs of the sensitive areas in the Zambezi, the environmental flows take the form of a smooth flood pulse parameterized by peak discharge, duration, and time of occurrence. Four distinct cases were analysed:

- C1. Varying environmental flood settings at Kariba and Itezhi-Tezhi. Results evaluated over the existing system (Kariba, Itezhi-Tezhi and Kafue Gorge dams, the Kafue Flats and the Mana Pools).
- C2. Varying turbine operation guidelines and environmental flood settings at Kariba and Itezhi-Tezhi. Results evaluated over the existing system (Kariba, Itezhi-Tezhi and Kafue Gorge dams, the Kafue Flats and the Mana Pools).
- C3. Varying environmental flood settings at Batoka Gorge, Kariba, and Itezhi-Tezhi. Results evaluated over the future system (Batoka Gorge, Kariba, Itezhi-Tezhi, Kafue Gorge and Kafue Gorge Lower dams, the Kafue Flats and the Mana Pools).
- C4. Varying turbine operation guidelines at Batoka Gorge, Kariba, and Itezhi-Tezhi, as well as environmental flood settings at Kariba and Itezhi-Tezhi. Results evaluated over the future system (Batoka Gorge, Kariba, Itezhi-Tezhi, Kafue Gorge and Kafue Gorge Lower dams, the Kafue Flats and the Mana Pools).

For each case, the free parameters were optimized resorting to a multiple-objective optimization algorithm that searches a Pareto set of optimal solutions with non-dominated trade-offs between energy production and flow alterations. AMALGAM (A Multi-Algorithm Genetically Adaptive Multi-objective method) (Vrugt and Robinson, 2007; Vrugt et al., 2009), a meta-optimization algorithm in the sense that it oversees the execution of four distinct multi-optimization algorithms, was chosen to this effect.

2.2 Simulation of dam operations

Dams were simulated in a conceptually simple manner, albeit with the key features that characterize real operations. The mass-balance equation that ruled dam operations is presented below:

$$V_{t+1} = V_t + P - E + Q_{in} - Q_{turb} - Q_{spill} \tag{4}$$

in it, V_t is the volume stored in the reservoir at time t, P is the rainfall over the reservoir (described by the average monthly values), E is the evaporation (described by the average monthly values), Q_{in} is the inflow, Q_{turb} represents the turbined outflow, and Q_{spill} the non-turbined discharge.

Rule curves, as well as volume-water height, volume-maximum discharge, and volume-surface functions were taken into account at each time step. The compliance to the rule curve was allowed to vary depending on the capacity of each reservoir and spillage is avoided whenever there is no danger of a fast rise of the water. This was done by promoting the adjustment to the rule curve trough a larger turbined flow rather than spillage. As the reservoir drops below the rule curve, the turbined flow is incrementally reduced as a means to prevent the complete halt of operations.

Environmental flows take the form of a smooth pulse which can be controlled by specifying timing, duration and magnitude. Similarly to turbining operations, environmental flows are reduced as the reservoir level drops below the rule curve. An example of the implemented procedure at work is illustrated in Figure 3. It covers a period where the Kariba reservoir is re-filling in the wake of an unusually dry period. It is worth noticing how the reservoir copes with this, by limiting turbining and environmental releases.

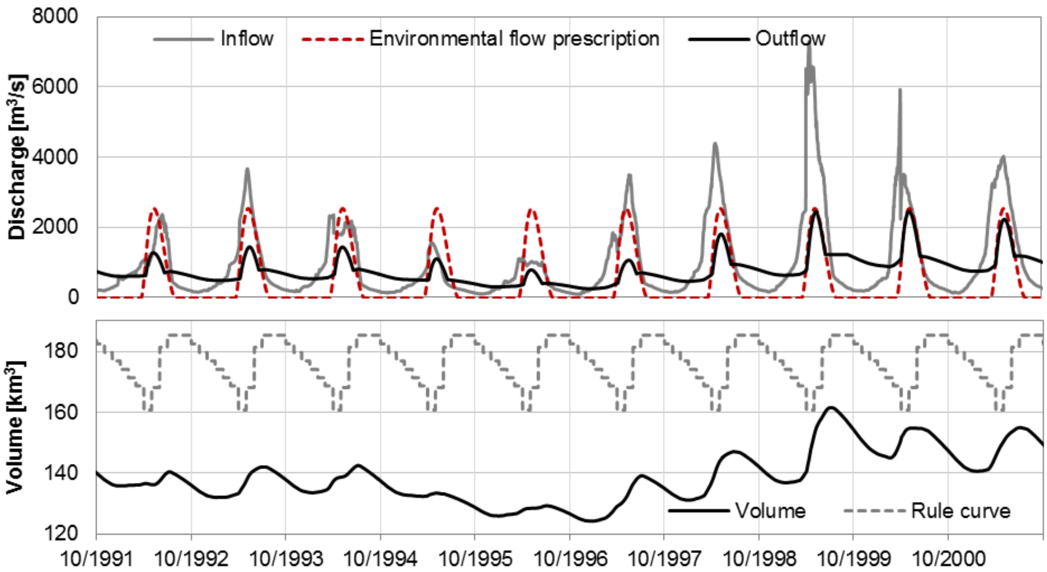

Figure 3. Example of simulated dam operations. Kariba dam, from Oct. 1991 to Sep. 2001.

2.3 Metrics for the analysis of operational prescriptions

In line with earlier work (Cohen Liechti et al., 2015), the scenarios were evaluated based on hydropower production and environmental criteria. The chosen hydropower production metrics were the annual energy production and the firm power (the amount of generated power matched or exceeded 95% of the year). Environmental criteria were based on Pardé coefficients (e.g. Cohen Liechti et al., 2014; Matos et al., 2010) and the Range of Variability Approach (RVA) proposed by (Richter et al. (1997). The flow was analysed according to magnitude, volume, timing, and duration:

- D_{Q30} – Discharge matched or exceeded 30 days during the year. Characterizes the annual flood peak;
- D_{Q335} – Discharge matched or exceeded 335 days during the year. Characterizes the low flow period;

- D_{VolQ30} – Volume of the discharge matched or exceeded 30 days during the year. Characterizes the annual volume;
- D_{DateQ1} – Date of the maximum discharge. Characterizes the timing of the annual flood peak;
- $D_{Dur\hat{Q}30}$ – Duration of the flood peak. Characterizes the duration of the annual flood peak, taken as the number of days in the year in which the flow is higher than a certain threshold. This threshold was taken as the 0.92 quantile of the observed discharge.

For each chosen indicator the degree of alteration is a function of the simulated years which fall within the band delimited by the 25th and 75th "unaltered or natural" percentiles. It is computed according to equation (5):

$$D_k = \frac{\left|N_k^o - N_k^e\right|}{N_k^e} \tag{5}$$

where D_k is the degree of alteration for indicator k, N_k^o is the number of years in which the indicator falls within the specified "natural" band, and N_k^e represents the expected number of years to be in the same range (in this case 50%).

The aggregation of the results for the various indicators and selected locations of environmental interest is done resorting to equation (6):

$$D = \frac{1}{N \cdot K} \sum_{i=1}^{N} \sum_{k=1}^{K} D_{k,i} \tag{6}$$

Where D stands for the total degree of alteration, N represents the number of locations, K is the number of indicators, and $D_{k,i}$ is the indicator D_k computed at location i.

2.4 Data

Inflow data was considered at Victoria Falls, Kamativi and Kafue Hook Bridge (Figure 4). Because the time series are not entirely concurrent within the analysed period, artificial series were generated for Victoria Falls and Kafue Hook Bridge. In order to do so, a novel non-parametric uncertainty characterization procedure, the Generalized Pareto Uncertainty (GPU) described in Matos (2014) was employed. The direct inflows from Kariba (approximately 15 to 20% of the total) were modelled based on the monthly discharge at Kamativi. The series was linearly converted to daily with a constraint on monthly discharge volumes; then variability was increased, and the data rescaled in order to match the aforementioned percentage of the inflows to Kariba. Results are illustrated in Figure 5. It should be emphasized that the artificial series generated are stationary, not accounting for climate change or the decadal climatic variability that has been observed in the past.

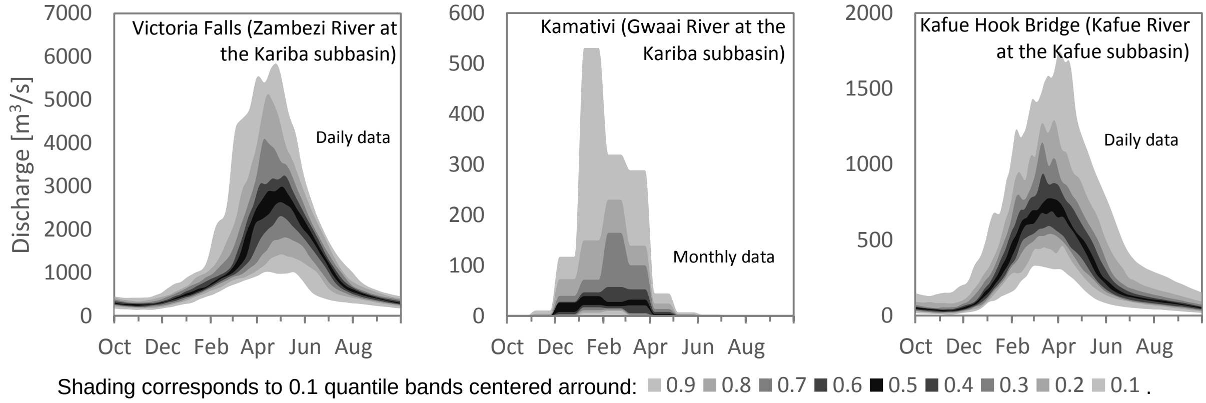

Figure 4. Synthesis of observed discharges at Victoria Falls, Kamativi, and Kafue Hook Bridge. Adapted from Schleiss and Matos (2016, in press)**.**

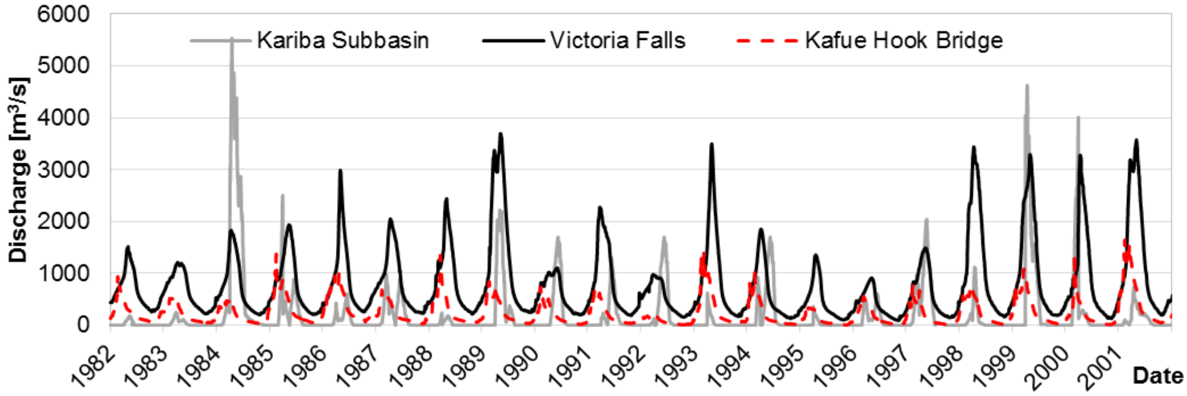

Figure 5. Adopted extended inflow series to the system.

3. RESULTS AND DISCUSSION

3.1 Existing infrastructure

The existing infrastructure was characterized by the mean annual energy production (Kariba, Itezhi-Tezhi, and Kafue Gorge) and the total degree of alteration (Kafue Flats and Mana Pools).

In the first of the two studied cases (C1), the magnitude, duration, and time of occurrence of the environmental flow pulses produced in Itezhi-Tezhi and Kariba were optimized. The optimization was conducted by AMALGAM, under which a total of 24 000 system evaluations were undertaken. The results are presented in Figure 6, where a trade-off between energy production and flow alteration can be clearly identified.

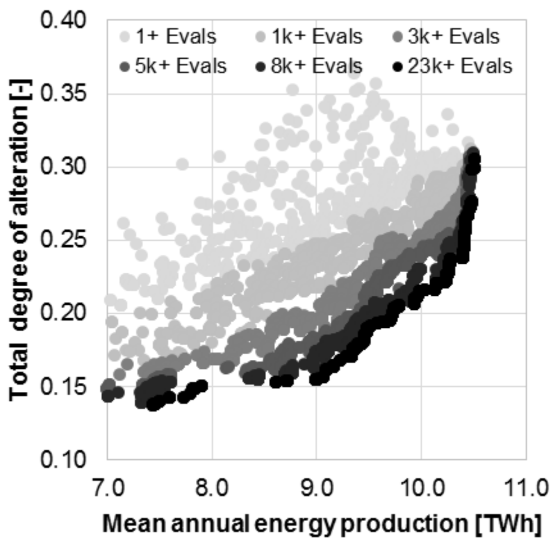

Figure 6. Pareto front of optimal solution obtained for case C1.

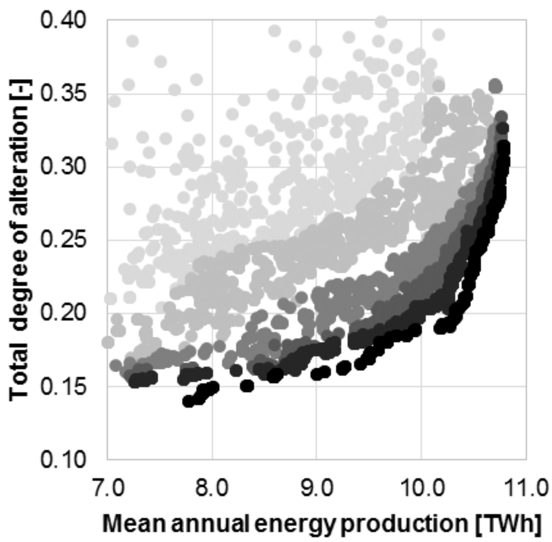

Figure 7. Pareto front of optimal solution obtained for case C2.

In the second case (C2), a similar procedure was adopted. Now, however, the base outflow at Itezhi-Tezhi, Kariba, and Kafue Gorge dams were made to vary as well. Being the aforementioned trade-off also present (see Figure 7), it is apparent that by modifying these extra variables better numbers of mean annual energy production can be achieved for similar flow alterations.

Initially, firm power was included among the multi-objective criteria. It was seen, however, that it can be strongly correlated to the mean annual energy production and, therefore, it was not optimized, but only evaluated.

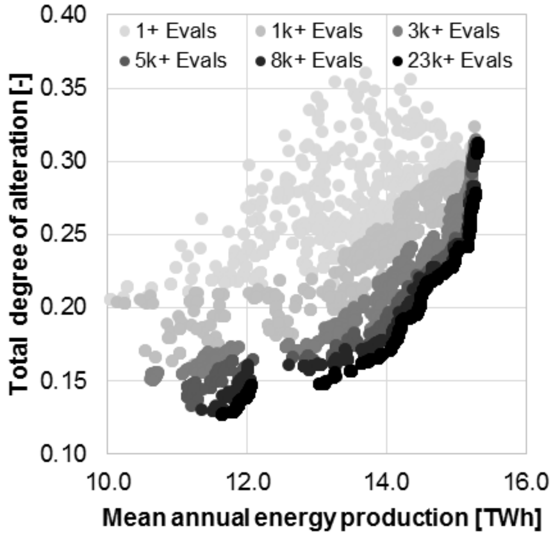

Figure 8. Pareto front of optimal solution obtained for case C3.

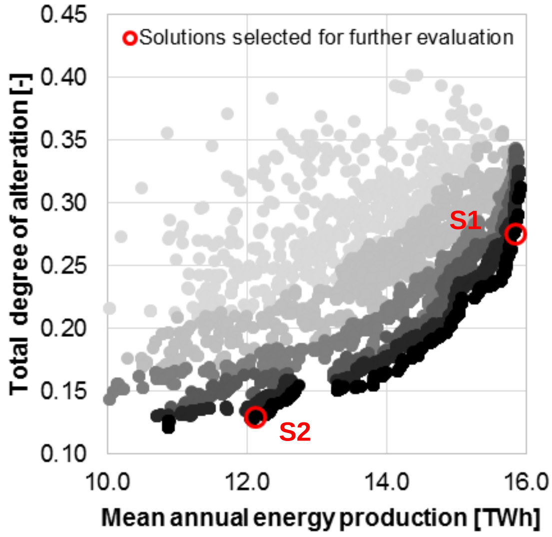

Figure 9. Pareto front of optimal solution obtained for case C4.

With mean annual energy productions in the range of 10 TWh, results fall in line with what is to be expected of the analysed system. They can, nonetheless, be improved in several ways, including: an increase in the number of simulated years; the simulation of the system through a specialized hydrological modelling software; the refinement of the admitted base outflows; the update of rule curves; a more elaborated environmental flow pulse shape; and a more sophisticated reservoir management algorithm that, for example, takes into account inflow forecasts.

3.2 Future developments

A similar analysis was made including planned additions to the hydropower infrastructure of the system. These are the Batoka Gorge and Kafue Gorge Lower dams, as well as power extensions at Kariba. All naturally add to the mean annual energy production.

Again, two cases were looked into: C3, where environmental flow pulses are optimized; and C4, where base outflows are also adjusted. Results are shown in Figure 8 and Figure 9, from which it can be again asserted that the adjustment of base outflows can yield significant gains in terms of energy production.

Going into detail, two optimal solutions for the system were chosen from case C4. These are solution S1, which privileges hydropower production, and solution S2, whose emphasis is on lowering environmental impacts. The distribution of RVA indicators for both cases and their comparison with natural flow values are presented in Figure 10.

Finally, the Pardé coefficients produced by solutions along the Pareto front for case C4 are depicted for the Kafue Flats (Figure 11) and the Mana Pools (Figure 12), where the natural flows' coefficients, as well as those of solutions S1 and S2 are also indicated.

From the results one can see that the annual flood at the Kafue Flats tends to be delayed regardless of the chosen solution. Most interestingly, it can be seen that a good quantification of the trade-off between hydropower production and flow alterations was achieved.

4. CONCLUSIONS

This contribution aimed to evaluate the impacts of different future hydropower development scenarios on the Zambezi River basin by employing a multi-objective optimization technique to characterize the trade-offs between environmental indicators and hydropower production.

Present and future development scenarios were evaluated under stationary hydrological inputs. Results clearly show that the methodology is useful in order to understand the "costs" of environmental flow pulses, as well as their impact on the downstream flow regimes.

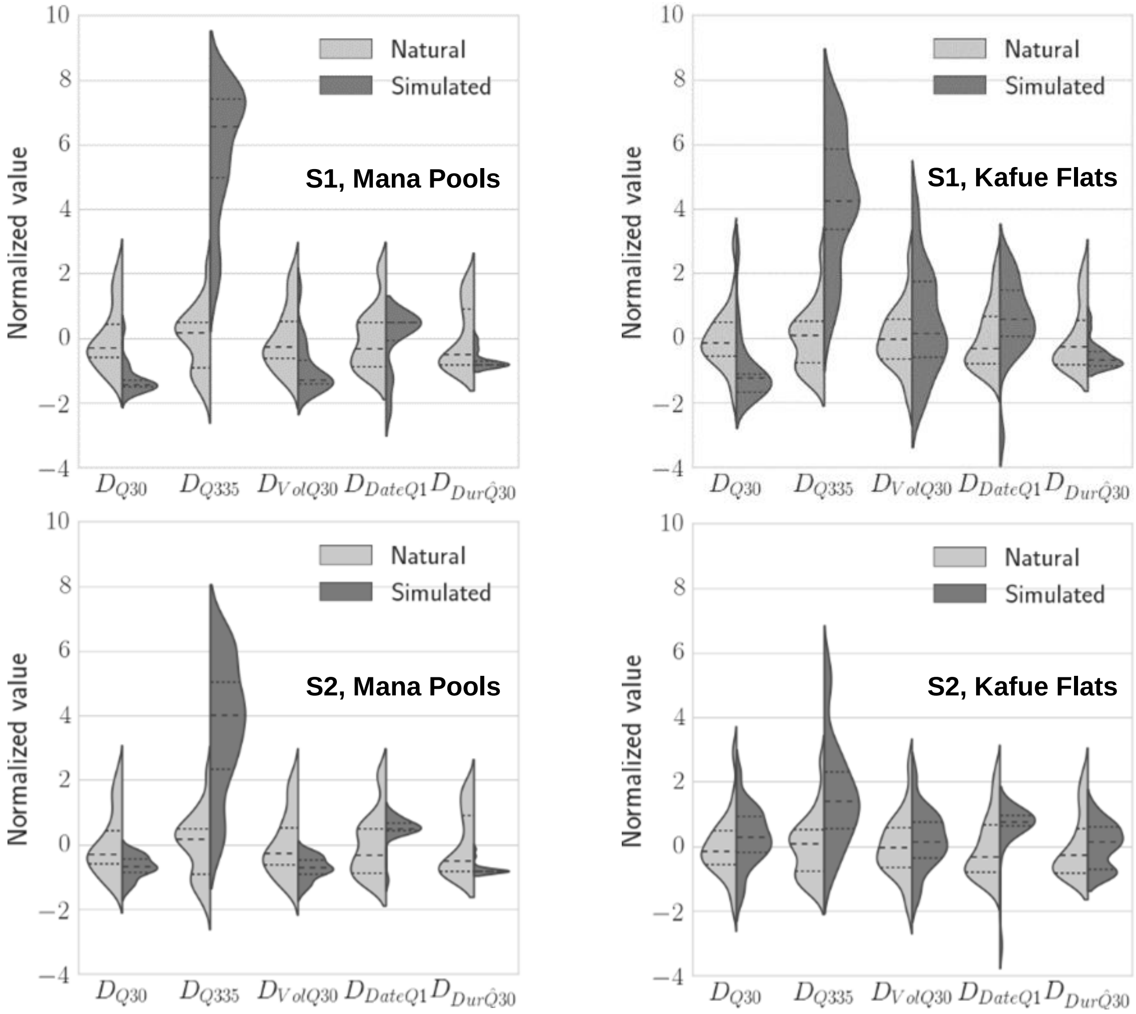

Figure 10. Dispersion of the chosen RVA indicators for two solutions of case C4. Lines within each density represent quantiles. Natural dispersion depicted in light grey; altered flow dispersion coloured in dark. Values normalized resorting z-scores based on the natural series.

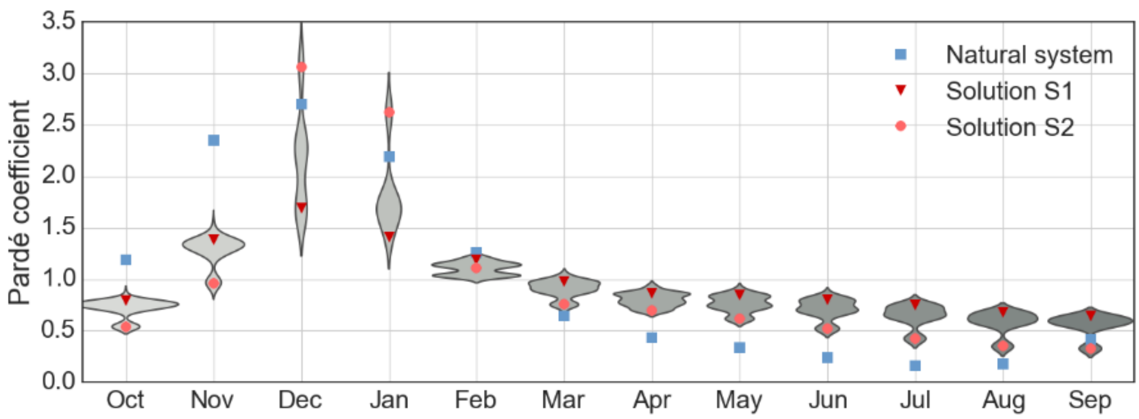

Figure 11. Distribution of Pardé coefficients for the optimal solutions of case C4 at the Kafue Flats.

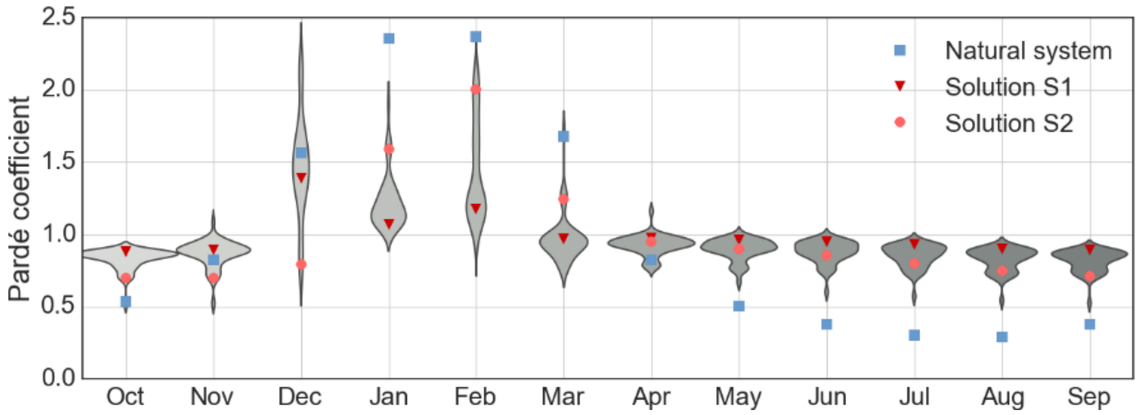

Figure 12. Distribution of Pardé coefficients for the optimal solutions of case C4 at the Mana Pools.

The followed approach is simple, leaving space for improvements. These can explore: an increase in the number of simulated years; the simulation of the system through a specialized hydrological modelling software; the refinement of the admitted base outflows; the update of rule curves; a more elaborated environmental flow pulse shape; and a more sophisticated reservoir management algorithm.

Future work can cover any of the aforementioned aspects. In addition, the methodology can be used in order to account for the impacts of climate change – predicted to have strong impacts on the Zambezi's flow regime – and a wider range of operational variables to be optimized.

5. ACKNOWLEDGMENTS

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